

On the nuclear reactions with participation of nearthreshold baryon resonances

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Abstract

The main features of nuclear reactions with participation of baryon resonances ($\Delta(1232)$, $S(1535)$ and $\Lambda(1405)$), which are interpreted as a manifestation of the bound states of nucleus and corresponding meson are discussed.

1 Pion-nuclear interaction in resonance energy region

In the first experimental works for π -meson interaction with nuclei in the energy diapason of the order of 100 MeV and higher the specific behaviour caused by the resonance nature of π -meson interaction with nuclear nucleon or with nuclei as whole were revealed. From the experimental point of view the reactions with simplest nucleus - deuteron, in particular, $\pi^+ + d \rightarrow p + p$, $\pi^+ + d \rightarrow \pi^+ + p + n$, πd -elastic scattering and others were most investigated. The reactions enumerated above are followed to common peculiarity: the behaviour of total cross-sections and others characteristics are corresponded to resonanced nature of πd - interaction at the energy about 150 MeV (in the c.m.s.). In particular, first experimental data obtained by M.G.Mescheryakov et al. [1] about behaviour of total cross - sections of $\pi^+ d \rightarrow pp$ reaction and inverse one show distinguishable maximum in this energy region (with the width of the order of 120 MeV). The analysis of angular distribution of π^+ -meson for $p + p \rightarrow d + \pi^+$ reaction points to P-wave meson production and besides that the angular distribution is the same with the increasing of π -meson energy by the factor two. This fact can indicate either on the equal ratio between $^1S_0 \rightarrow ^3S_1$ and $^1D_2 \rightarrow ^3S_1$ transitions to whole considered energy diapason and amplitudes for these transitions should be equally depend on the energy or the dominant role plays one of these transitions.

Experimental data could be qualitatively explained if one take into account that the π -meson interaction has a resonance behaviour in the state with spin

and isospin are equal 3/2 (isobar Δ_{33}) In this case the main contribution to P-wave π -meson production will be caused by $^1D_2 \rightarrow ^3S_1$ transition. There are two possibilities for explanation of resonance maximum in the reactions $pp \rightarrow d\pi^+$ and $\pi^+d \rightarrow pp$: either two-nucleon interaction in 1D_2 -state has resonance nature, i.e. so called "dinucleon resonance" is formed (in other terminology - simplest "isonucleus" or " π - mesonucleus") or this process takes place throw the virtual production of Δ_{33} -isobar.

The theoretical consideration of these reactions in the assumption of virtual isobar-nucleon state was carried out in [2], where triangle Feynman diagram with virtual isobar was calculated and it was shown that the energetical behaviour near complex singularity of considered diagram could immitate resonance behaviour of total cross - section for $\pi^+d \rightarrow pp$ reaction. In this case angular distribution of π -meson is caused by dominant contribution of S-wave in the relative motion of Δ_{33} and nucleon. By the analogy resonance behaviour of $\pi^+d \rightarrow pp$ reaction in the energy region near 2.84 GeV could be explained by the virtual production of $\Delta(1920)$ [3].

As for the experimental investigation of πd elastic scattering in resonance region i.e. at the π -meson energies of the order of 200 MeV (in the l.s.) it was also revealed the existence of distinguishable maximum in the total cross - section. Observed maximum in the total cross - section and ratio $(\sigma(\pi^-d) - \sigma(\pi^-p)) / \sigma(\pi^-p) \approx 3$ indicate on virtual Δ_{33} -nucleon production.

On the language of Feynman diagrams this mechanism is corresponded to the calculation of nonrelativistic squared diagram. The total and differential cross - sections of πd elastic scattering were calculated with this diagram [4]. Resonance behaviour is caused by singularities of this diagram which lie near physical energy region. The comparison with experimental data show rather well agreement (some differences between the calculations correspond to the different deuteron form-factors at the relatively large (> 150 MeV/c) relative momenta). Precision investigation of differential cross - section could be used as a criterium between two possible explanations for observed resonance maximum: a) formation of two - nucleon resonance ("isonucleus" or "mesonucleus") with $B = 2$ and b) enchancement mechanism due to singularities of Feynman diagrams just near physical region of kinematical variables.

Thus the exact conclusion about the existence of simplest "isonucleus" (or "mesonucleus") is not possible to make from the contemporary experimental data and theoretical works since it is necessary to exclude the contribution of peripheral mechanisms which are corresponded to Δ_{33} -nucleon virtual state.

As for the interaction of π -meson with complex nuclei the interesting experimental observation was made for the reaction $\pi^-^{12}C \rightarrow \pi^-n^{11}C$ where the resonance maximum in the total cross - section at the kinetic π -meson energy of the order of 200 MeV (in the l.s.) was observed [5]. Using the well known theory of direct nuclear reactions the analysis of this reaction was made [6]. The behaviour of total cross-section at π -meson energies more than 200 MeV was well quantitatively described by the single nucleon mechanism (pole ap-

proximation) for the production of Δ_{33} and its following decay to π -nucleon channel. However in the low energy region (< 200 MeV) there is significant discrepancy between experimental data and calculations with pole approximation. Finally, maximum in the total cross-section for the $^{12}\text{C}\pi^- \rightarrow \pi^- n^{11}\text{C}$ reaction was found to be wider and shifted in comparison with pole approximation.

The reason for this discrepancy (as it was shown [7]) could be consist in the assumption that not only pole diagram is distinguished in this energy region. Namely, one can be noted that the triangle diagram, which corresponds to elastic scattering of Δ_{33} on ^{11}C , has the singularity just near physical region of kinematical variables. In this case we deal with the complex singularity at the energy (in the c.m.s.) is equal to the sum of the masses of Δ_{33} and ^{11}C nucleus. Taking into account the contribution of pole and triangle diagrams the rather well description of the experimental data was obtained. In particular, the broadening of resonance maximum and its shift (of the order of 30 MeV) to the region of smaller energy of incident π -mesons were explained. Note, that the contribution of diagram with rescattering of Δ -isobar on intermediate nucleus looks like as interaction of "stopped" isobar with ^{11}C nucleus.

Thus the present experimental data and theoretical considerations leave the question open on the existence of "isonuclei". In each concrete case it is necessary to carry out the complex of experimental and theoretical investigations to separate the effects of nuclear reaction mechanism from the formation of "isonuclei" i.e. bound state of isobar (or - π -meson) with nucleus. First of all it is needed to investigate the angular distributions and polarized characteristics.

2 η -nuclei

At present there are considerable experimental data and theoretical investigations on the possible existence of η -meson-nucleus bound states or " η -nuclei". Detailed review of present situation was done in [8]. Difficulties in interpretation of experimental data consist in the production type mechanism for η -meson on free nucleon which has threshold character and is determined by the production of $S_{11}(1535)$ baryon resonance and its following decay to πN or ηN with equal probabilities. Most convinced data on the photoproduction of $S_{11}(1535)$ on nuclei were obtained using the beam of γ -quanta from electron synchrotron (FIAN). The spectrum of correlated $\pi^+ n$ pairs arising from $\gamma + ^{12}\text{C} \rightarrow \pi^+ nX$ and flying transversely to photon beam have been observed [9]. The main result consists in observation of the shift for resonance maximum in $(\pi^+ n)$ system in comparison with Table value for $S_{11}(1535)$.

In view of these experimental data one could takes notice of the following:
a. observed shift in the position of $S_{11}(1535)$ in the reaction $\pi^+ + ^{12}\text{C} \rightarrow \pi^+ nX$ looks like as the same phenomenon for production of $\Delta_{33}(1232)$ in the reaction $\pi + ^{12}\text{C} \rightarrow \pi\text{NX}$. In the last case observed shift could be explained by the possible nuclear reaction mechanism for production of Δ_{33} on nucleus.

This mechanism includes triangle Feynman diagram with rescattering Δ_{33} on intermediate nucleus besides pole diagram corresponded to the production on the bound nucleon. Taking into account these two diagrams it was turn out to explain the broadening and shift of Δ_{33} in production on nuclei. Note that in rescattering processes as a propagator for virtual Δ it is necessary to use a pole position in the πN amplitude which corresponds to smaller mass in comparison with the value on mass shell ($\text{Re } M(\Delta_{33}) = 1210 \text{ MeV}$ for $\Delta_{33}(1232)$). The same pole position for $S_{11}(1535)$ is equal to $\text{Re } M(S_{11}) = 1500 \text{ MeV}$. At the same time the position of complex singularity is determined by the sum of $\text{Re } M(\text{resonance})$ and mass of nucleus. To clear up a nuclear reaction mechanism for photoproduction of $S_{11}(1535)$ on nuclei the additional experimental and theoretical efforts are needed. As for the one nucleon mechanism (pole diagram) this question was considered in details in [10]. In particular an investigation of small transvers momentum region for $(\pi^+ n)$ pairs gives possibility to use the Treiman - Yang criterium [11].

In view of considered above the investigation of peripheral mechanisms for production of $S_{11}(1535)$ on nuclei can give additional information about the phenomena connected with the formation of η -nuclei on the background of peculiarities of the nuclear reaction mechanism.

3 K - nuclei

By the analogy with the cases considered above the existence of nearthreshold $\Lambda(1405)$ baryon resonance determining low energy KN - interaction as input for hypothesis about possible formation of nearthreshold K - nucleus bound states was used.

In the work [12] phenomenological potential model for K-meson interaction with light nuclei was proposed. For elementary KN-interaction a potential approximation with simplest Gaussian form for interaction potential was used. The parameters of KN - potential were choosed so to obtain correct KN scattering lengths known from the shifts and widths of K^-p and K^-d atoms and to reproduce the mass of $\Lambda(1405)$ as a bound state of K-meson and nucleon. Using obtained so two-body KN - potential the optical potential for K - nucleus interaction was calculated. With this optical potential the existence of ${}^3_K H(I=0,1)$ and ${}^4_K H(I=1/2)$ bound states with binding energies from 20 MeV up to 100 MeV and widths of the order several tens MeV were predicted.

The proton and neutron energy distributions from $\text{He}(\text{stopped } K^-, N)$ reactions were measured in [13]. In the missing mass spectrum two mono-energetic peaks were observed. These peaks were interpreted as the formation of tribaryon $S^0(3115)$ and $S^+(3140)$ with isospins $I=0$ and 1 and strangeness $S=-1$, correspondingly. In the potential model considered in [12] these states should correspond to the bound ${}^3_K H(I=0)$ and ${}^3_K H(I=1)$ states. Binding energies for these states (200 MeV) turned out to be larger and widths smaller ($< 20 \text{ MeV}$)

than theoretically predicted. Nevertheless taking into account statistical significance (13σ for S(3115) and 3.7σ for S(3140)) these experimental results really indicate on the possible existence of three-body K-nuclei. Another interpretations of these data are not so convincing (for instance, the interpretation as the ΣNN hypernuclei is less probable since excitation energies for these hypernuclei should be of the order 50 MeV or higher).

As the direct test to prove the existence of bound K-nuclei it will be useful to observe the discrete spectra of γ -quanta or π -mesons injected due to transitions from states of K^- -He atom to one of the states of three-body K-nucleus. Simple estimations give for the probabilities of radiative transitions the value of the order of $10^{-3} - 10^{-4}$ and in the case of probabilities for π -meson transitions will be $10^{-1} - 10^{-2}$, correspondingly.

In conclusion, it would be note that the question on the existence of new kind of nuclei with meson as a constituent is a great of interest. However the interpretation of present experimental data is not so simple. From our point of view the reasons are either in the necessity of experimental confirmation for obtained data (for instance, in the case of K -nuclei) or in the additional experimental and theoretical analysis. In particular the question about possible nuclear reaction mechanism should be especially checked. Here we are not considered the predictions of quarks model in which the rich spectrum of multiquark states are predicted [14] since to speak about quark nature of the states considered above without identification even if one of ground states looks like as prematurely.

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